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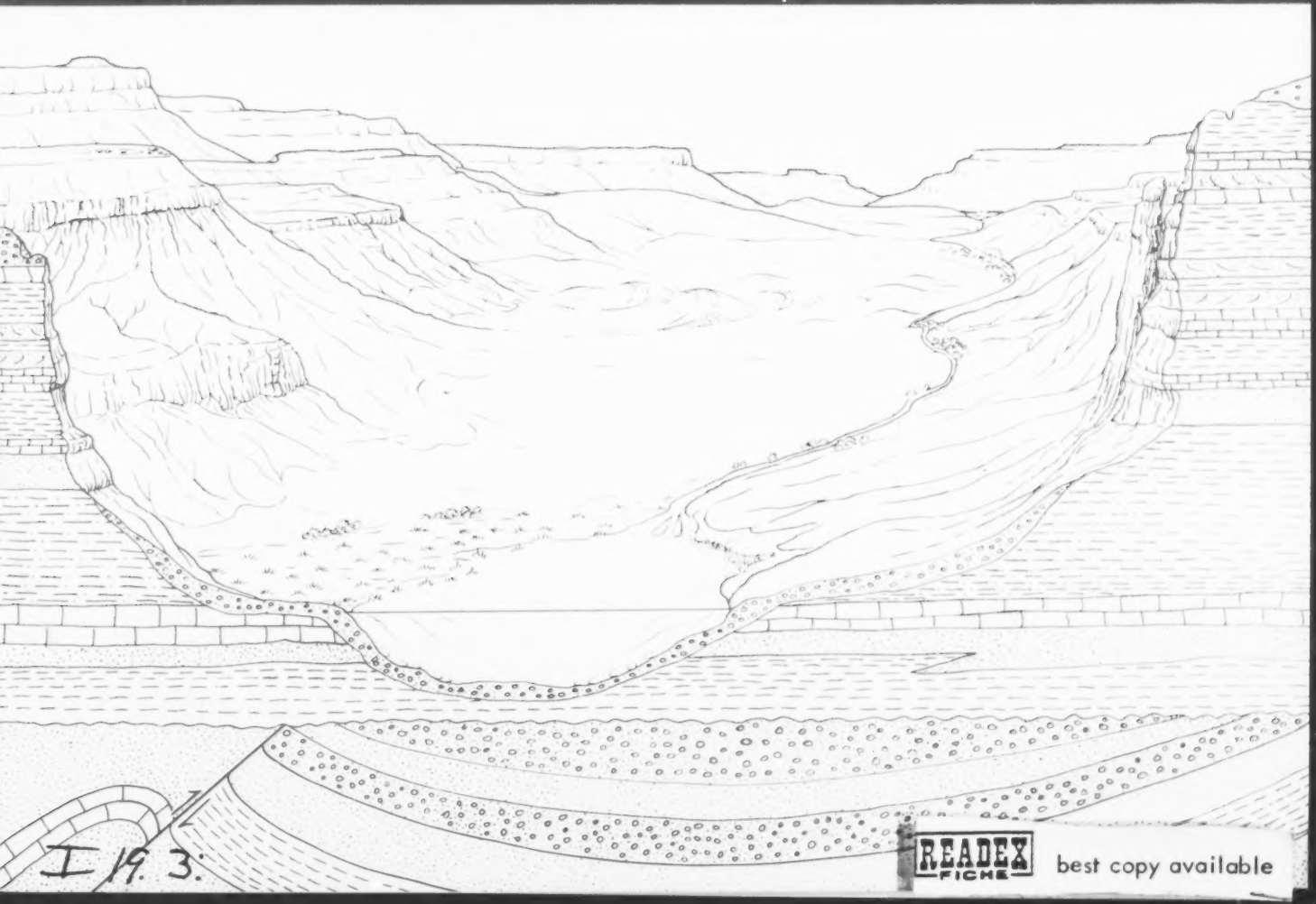
In Situ Stress Analysis of Wellbore Breakouts from Oklahoma and the Texas Panhandle

U.S. GEOLOGICAL SURVEY BULLETIN 1866–F



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Chapter F

In Situ Stress Analysis of Wellbore Breakouts from Oklahoma and the Texas Panhandle

By RICHARD L. DART

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1866

EVOLUTION OF SEDIMENTARY BASINS—ANADARKO BASIN

DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

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In Situ Stress Analysis of Wellbore Breakouts from Oklahoma and the Texas Panhandle

By Richard L. Dart

Abstract

Orientations of crustal stresses are inferred from stress-induced breakouts (wellbore enlargements) in the eastern part of the Anadarko basin in central Oklahoma, the Marietta basin in south-central Oklahoma, and the Bravo dome area of the central Texas Panhandle. Inferred directions of maximum horizontal principal stress (SH_{max}) are east-northeast for the eastern Anadarko basin and northeast for the Marietta basin and the Bravo dome area.

The relative magnitudes of the three principal stresses (S_1, S_2, S_3) are known for the Bravo dome area from existing hydraulic-fracturing measurements, and a normal-faulting stress regime ($S_V > SH_{max} > SH_{min}$) is implied. For the eastern Anadarko basin and the Marietta basin, the magnitudes of the principal stresses are not known. Possible left-lateral oblique slip on the Meers fault during the Quaternary implies that strike-slip ($SH_{max} > S_V > SH_{min}$) and reverse ($SH_{max} > SH_{min} > S_V$) faulting has occurred in south-central Oklahoma. Thus, the study region may be a transition zone between extensional stress in the Texas Panhandle and compressional stress in Oklahoma.

Breakout data from the eastern Anadarko basin yield a single consistent SH_{max} orientation, whereas data from the Marietta basin and the Bravo dome area yield bimodal-orthogonal distributions believed to consist of northwest-oriented breakouts and northeast-oriented fracture-related wellbore enlargements. This northeast (orthogonal) trend in data from the Marietta basin and the Bravo Dome area is probably related to drilling-induced hydraulic fracturing of the wellbore or to preexisting natural fractures or joint sets intersecting the wellbore. On dipmeter log records, breakouts and fracture-related enlargements have similar elliptical cross sections. Orthogonally oriented breakout and fracture-related wellbore enlargements are therefore differentiated by comparing their long-axis orientations with directions of known or inferred horizontal stress.

The mean orientations of either the breakout or fracture-related orthogonal trends in the Marietta basin and the Bravo dome area data sets are not as well constrained as the mean orientation of breakout data for the eastern Anadarko basin. Poorly constrained mean orientations give the appearance of data scatter or dispersion among wellbore enlargement orientations within the northwest and northeast bimodal-orthogonal trends. Drill holes in the Marietta basin and Bravo dome area are located primarily between northwest-striking subparallel faults. Mean data orientations calculated for either orthogonal trend for individual well data sets appear to rotate counterclockwise across these two fault-bounded study areas. Stress trajectory rotation between suparallel faults within the Marietta basin and the Bravo dome study areas may account for the data scatter.

Although breakouts and fracture-related enlargements formed in all parts of the thick sequences of sedimentary rocks logged, they are primarily in limestone, shale, and dolomitic rock, probably because of the abundance of these rock types.

Manuscript approved for publication, January 10, 1990.

INTRODUCTION

Numerous borehole stress studies (Cox, 1970; Brown, 1978; Bell and Gough, 1979, 1982; Gough and Bell, 1981, 1982; Hickman and others, 1985; Plumb and Hickman, 1985; Teufel, 1985; Zoback and others, 1985) and theoretical and laboratory studies simulating borehole stress conditions (Mastin, 1984; Haimson and Herrick, 1985; Zoback and others, 1985) show that wellbore breakouts are stress-induced spall zones that typically elongate vertically within the wellbore and are the result of compressional shear failure of the wellbore associated with unequal horizontal compressive stresses about the wellbore. Wellbore breakouts are elliptical in cross section and are aligned in the direction of minimum horizontal compressive stress (SH_{min}). The idea that breakouts reflect local in situ stress conditions is supported by the agreement between stress directions

inferred from breakouts and stress orientations obtained using other types of stress data such as earthquake focal mechanisms, hydraulic-fracturing measurements, and geologic indicators of stress (Gough and Bell, 1981, 1982; Hickman and others, 1985; Plumb and Hickman, 1985; Dart and Zoback, 1989).

Breakout-data analysis is an important tool in understanding present-day stress conditions in areas where more detailed stress measurements are not available. An understanding of in situ stress conditions is essential in evaluating seismic hazards, recent crustal deformation, and the potential for slip on existing faults. In the petroleum industry, knowledge of borehole stress conditions can be critical in the engineering and design of drilling operations and hydraulic-fracturing treatments (Dart and Zoback, 1989).

The eastern Anadarko basin, Marieta basin, and Bravo dome area were selected for study on the basis of data availability, proximity to the Anadarko basin, and involvement in the structural and tectonic evolution of Oklahoma and the Texas Panhandle. This paper offers a more detailed analysis of data presented in earlier reports (Dart, 1987; Dart and Zoback, 1987).

Acknowledgments.—I thank the following individuals and companies for the generous assistance in acquiring much of the data needed for this study: David Walker (Baker and Taylor Drilling Co., Amarillo, Tex.); Mark Ramsey and E.G. Kerns (Cities Service Oil and Gas Corp., Oklahoma City, Okla.); Bill Osten (Phillips Petroleum Co., Oklahoma City, Okla.); T.A. Deines, Stephen O'Niell, and P.L. Clymer (Marathon Oil Co., Midland, Tex.); J.A. Norton (Consolidated Oil and Gas, Inc., Denver, Colo.); Greg Riepl (States Petroleum Inc., Irving, Tex.); D.J. Wechsler, Daniel Hanson, and M.D. Wittstrom (Chevron U.S.A. Inc., Oklahoma City, Okla.); Jackie Ritchey and Bill Clement (AnSon Gas Corp., Oklahoma City, Okla.); Ted Price (Samedan Oil Corp., Oklahoma City, Okla.); S.A. Maier (The Anchutz Corp., Oklahoma City, Okla.), Phil Schrenier and A.R. Dowell (Texaco U.S.A., Denver, Colo.); and Tom Verolust (Mustang Production Co., Oklahoma City, Okla.).

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GEOLOGIC SETTING

Located on the boundary between the Great Plains and Central Lowlands physiographic provinces, the study area (fig. 1) is a region of deep sedimentary basins filled with thick sequences of Paleozoic marine rocks separated by uplifted basement structures of Cambrian and Precambrian igneous and metamorphic rocks (Jordan, 1967; Johnson and others, 1972; Johnson and Denison, 1973; Johnson and others, 1984). The primary west-northwest structural trend of basins and basement highs extends across southern Oklahoma into the Texas Panhandle. This trend developed in the Paleozoic Era during periods of basement faulting, igneous intrusion, basin subsidence, and orogenic deformation (Ham and others, 1964; Hoffman and others, 1974; Wickham, 1978; Perry, 1989). The stratigraphic history of the region is dominated by episodes of carbonate and shale deposition attributed to eustatic fluctuations and intervals of clastic deposition associated with subareal erosion of uplifted areas.

The eastern Anadarko basin underlies most of central Oklahoma (figs. 1 and 2). It is bounded on the south by the Amarillo-Wichita uplift, the Marietta and Ardmore basins, and the Arbuckle uplift and on the east by the Nemaha ridge. The Frontal fault system forms a reverse-faulted zone of detachment that separates the Anadarko basin to the north from the Amarillo-Wichita uplift (Gilbert, 1983; Perry, 1989). The basin is deepest along this boundary; an accumulation of more than 40,000 ft of Paleozoic sediments forms the most complete Paleozoic section in the Midcontinent structural province (Adler and others, 1971). This Cambrian to Permian section is composed of Cambrian to Mississippian carbonate rocks and shale unconformably overlain by Pennsylvanian to Permian clastic sedimentary rocks (Petroleum Information Corporation, 1982). The lower part of this section formed during a period of shallow marine deposition and rapid basin subsidence (Feinstein, 1981); the upper part was deposited in response to erosion of the Amarillo-Wichita and Criner uplifts to the south and east of the basin (Moore, 1979). Faulting along the eastern and southern boundaries of the basin occurred during the formation of the Amarillo-Wichita uplift and in response to compressional tectonism associated with uplift of the Ouachita Mountains and the Nemaha ridge (fig. 1) (Gilbert and Donovan, 1982; Burchett and others, 1985). Evidence of recent movement on faults within the Frontal fault system in southern Oklahoma is supported by geomorphic and stratigraphic data. Ramelli and others (1987) and Luza and others (1987) have documented Quaternary oblique slip with down-to-the-south movement on the Meers fault and possible recent movement on the Washita Valley fault.

The Marietta basin in Oklahoma (figs. 1 and 3) at the eastern end of the Amarillo-Wichita uplift is within the Southern Oklahoma aulacogen. This northwest-trending synclinal structure is bounded on the northeast by the Criner uplift and on the southwest by the Waurika-Muenster uplift. The early depositional history of this area, which predates the formation of the Marietta

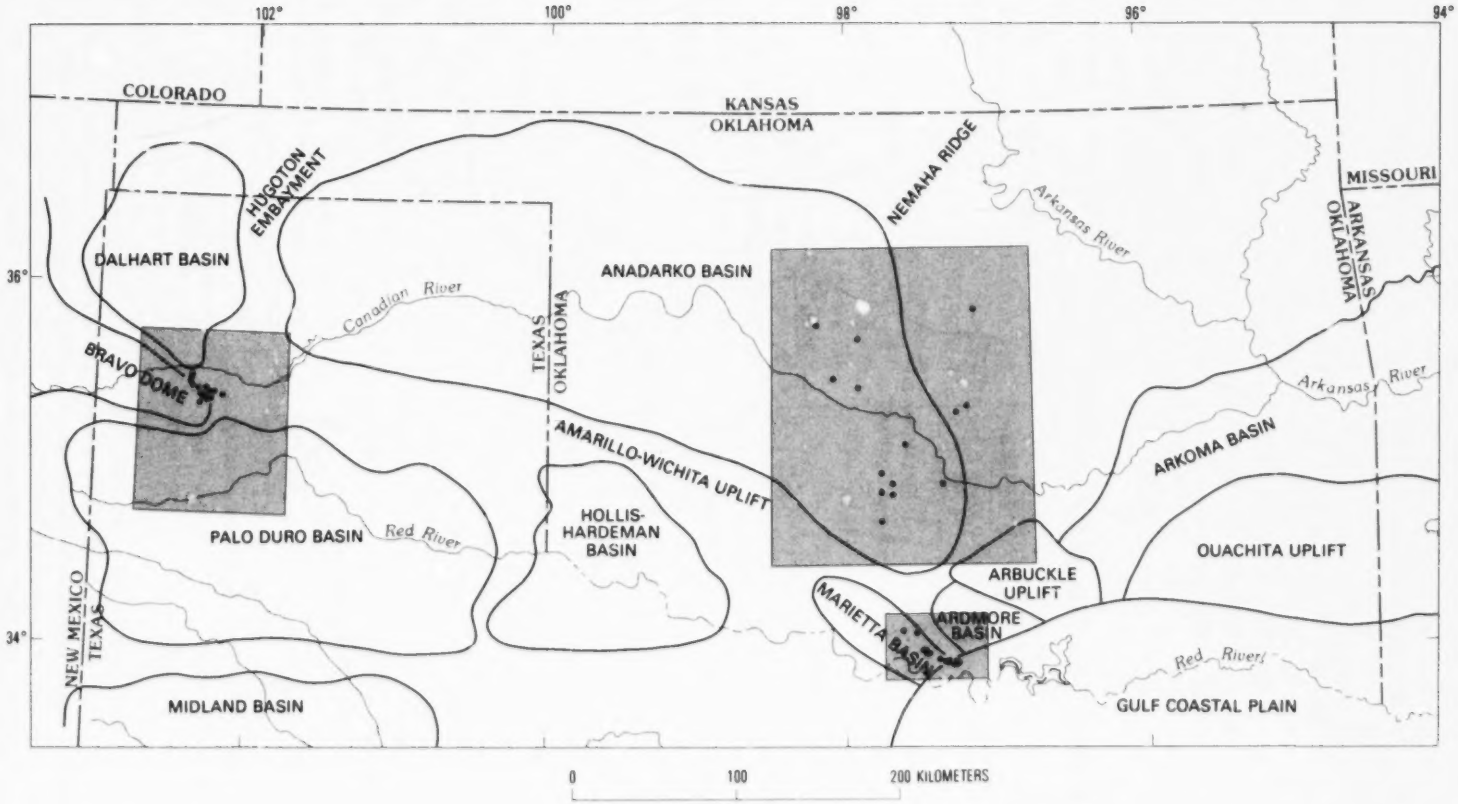
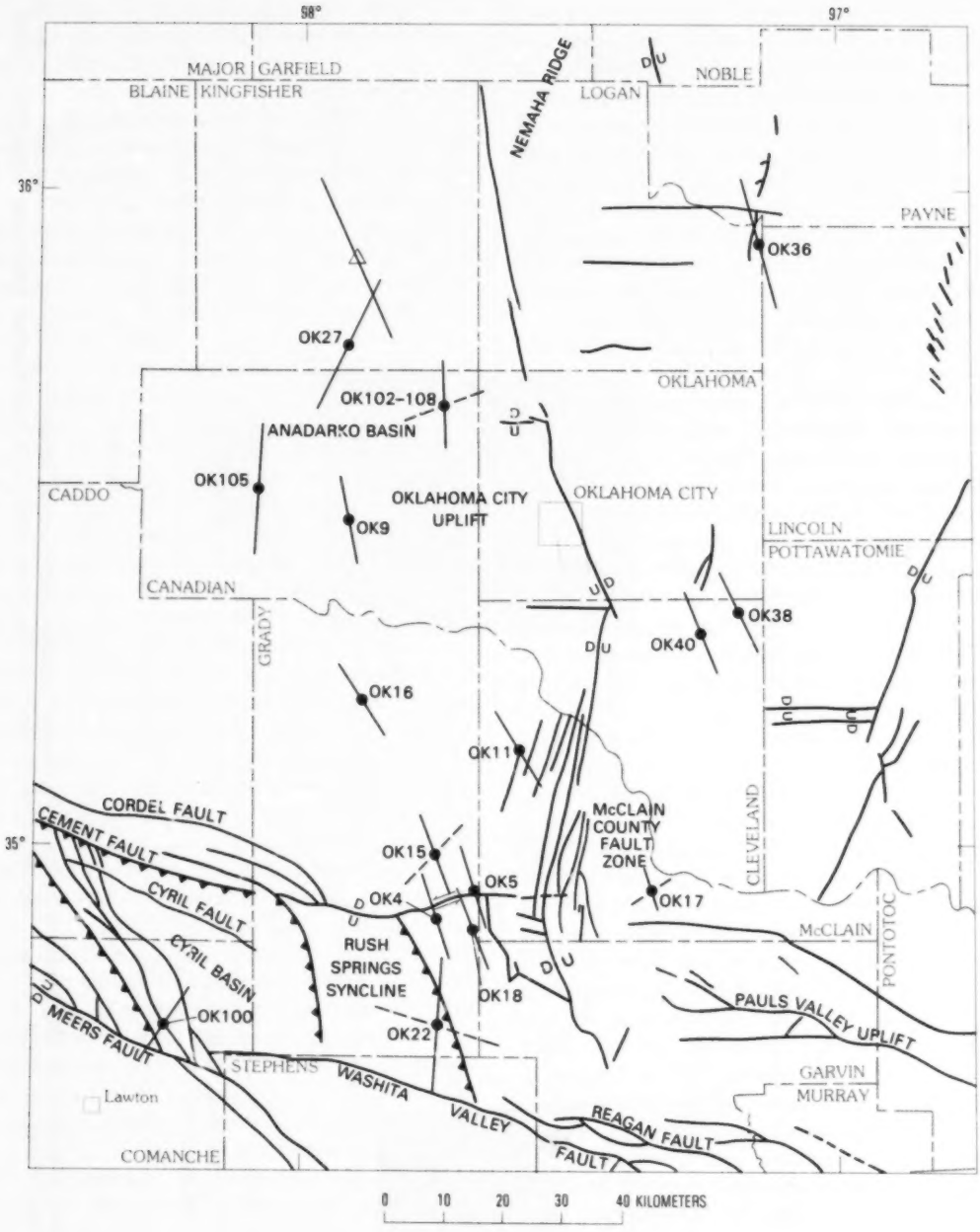


Figure 1. Generalized structure of Oklahoma and the Texas Panhandle. Location of study areas (screened areas) and wells used (solid dots) are also shown. Modified from Nicholson (1960), Johnson and others (1972), Morris (1974), Haley (1976), and the Petroleum Information Corporation (1983).



EXPLANATION

Thrust fault—Sawteeth on upper plate

Strike-slip fault—Arrows indicate relative horizontal movement

Dip-slip fault—Upthrown (U) and downthrown (D) blocks shown

Fault—Dashed where inferred

F4 Evolution of Sedimentary Basins—Anadarko Basin

syncline, involves deposition of a thick sequence of Cambrian to Ordovician carbonate rocks overlain by Upper Ordovician through Lower Mississippian limestone, sandstone, and shale (Henry, 1968).

The Wichita orogeny in Late Mississippian to Middle Pennsylvanian (early Atokan) time and the Arbuckle orogeny in early Desmoinesian to early Virgilian time were significant events in the structural and depositional histories of the Marietta basin (Tomlinson and McBee, 1959). Formation of the Criner and Muenster-Waurika uplifts and faulting and folding associated with initial development of the Marietta syncline accompanied the Wichita orogeny (Tomlinson and McBee, 1959). Early syncline development is possibly associated with deformation of the Southern Oklahoma aulacogen (Wickham, 1978). Significant deposition within the syncline did not begin until late Middle Pennsylvanian (Desmoinesian) time (Frederickson and Redman, 1965). The Marietta syncline was little affected by tectonism of the Arbuckle orogeny. During this period of orogenic activity, the Criner uplift acted as a structural barrier to southwest compressional stresses and associated crustal shortening and faulting (Frederickson and Redman, 1965). At the close of the Pennsylvanian Period, however, Virgilian- and Permian-age sediments were eroded from the Arbuckle Mountains and deposited over the area (Frederickson and Redman, 1965). Basin subsidence associated with sediment loading continued into post-Permian time (Frederickson and Redman, 1965).

The Bravo dome (figs. 1 and 4), located within the larger Permian basin, is a Late Mississippian to Early Pennsylvanian tectonic feature between the Dalhart and Palo Duro basins (Budnik and Smith, 1982). Formation of the Bravo dome coincided with development of the Amarillo-Wichita uplift. By mid-Permian time, carbonate and clastic (arkosic) sedimentary rocks deposited in response to Late Mississippian to Early Pennsylvanian tectonism completely covered structural features such as the Bravo dome and filled the smaller basins in the region (McGookey and Goldstein, 1982). Within this part of the Texas Panhandle, a sequence of Permian-age halite-bearing formations interbedded with marine mudstone, siltstone, anhydrite, and dolomite units covers the Bravo dome structure (Presley, 1980). This overlaying sedimentary accumulation is cut by a series of northwest-striking high-angle faults that define basement structures (fig. 4) (Dutton and others, 1982). The most prominent of these is the Potter County fault, which separates the Bravo dome from the Dalhart basin. Basement faults associated with Paleozoic tectonism of the Amarillo-Wichita uplift are probably reverse faults (Dutton and others, 1982). Deformation, associated with these faults, of late Tertiary-age Ogallala Formation strata is indicative of Cenozoic fault movement in the Texas Panhandle (Budnik, 1987).

Figure 2 (facing page). Structure map of the eastern Anadarko basin. Direction of wellbore enlargement is indicated by dot with solid line; line length is proportional to statistical quality (A–C); for example, OK27 is B quality, and OK16 is C quality. Bimodal-orthogonal data sets and data sets that are not bimodal but do have orthogonal data are indicated by paired solid lines and paired solid and dashed lines, respectively. Line lengths for some bimodal-orthogonal and orthogonal data sets are commonly shorter because of D-quality standard deviations. Open triangle with line indicates hydraulic fracturing data (von Schonfeldt and others, 1973). Structural features from Chenoweth (1972).

WELLBORE ENLARGEMENT DATA

Wellbore enlargement (breakout) stress data are the measured long-axis orientations of stress-related elliptical features on standard four-arm, high-resolution dipmeter and fracture-identification well logs. Breakout-stress studies are economical because of the availability of well-log data through institutional, commercial, and industrial sources.

Two types of wellbore enlargements are important to this study: (1) stress-induced breakouts associated with shear failure of the wellbore, and (2) orthogonally oriented, stress-related fracture borehole enlargements likely associated with either drilling-induced hydraulic fracturing of the wellbore or favorably oriented preexisting fractures or closely spaced joint sets intersecting the wellbore (fig. 5) (Dart and Zoback, 1989). Fracture-related wellbore enlargements should be oriented in the direction of SH_{max}, perpendicular to the trend of breakouts in the same well, creating an orthogonal-bimodal distribution of enlargement orientations. Fracture-related enlargements due to preexisting fractures reflect the trend of these fractures. Whether hydrostatically induced or preexisting, fractures intersecting the borehole probably aid in the formation of stress-related, elliptically shaped wellbore enlargements.

Statistically, wellbore enlargement data sets are treated as axially symmetric, circular-normal distributions of two-dimensional vectors (Batschelet, 1965; Dart, 1987). The results of standard statistical calculations for mean direction, mean deviation, and standard deviation are displayed as rose diagrams of data sets (figs. 6–8). To avoid having the analyst or the reader make biased interpretations of inferred stress orientations, rose-diagram plots are proportional to petal area, not petal length (Werner, 1976).

In the three areas studied, borehole data from a total of 46 selected wells consisting of 40 well data sets (tables 2–4) were analyzed. Only well data sets having statistical qualities of C or better (table 1) (M.L. Zoback, written commun., 1987) and bimodal-orthogonal and

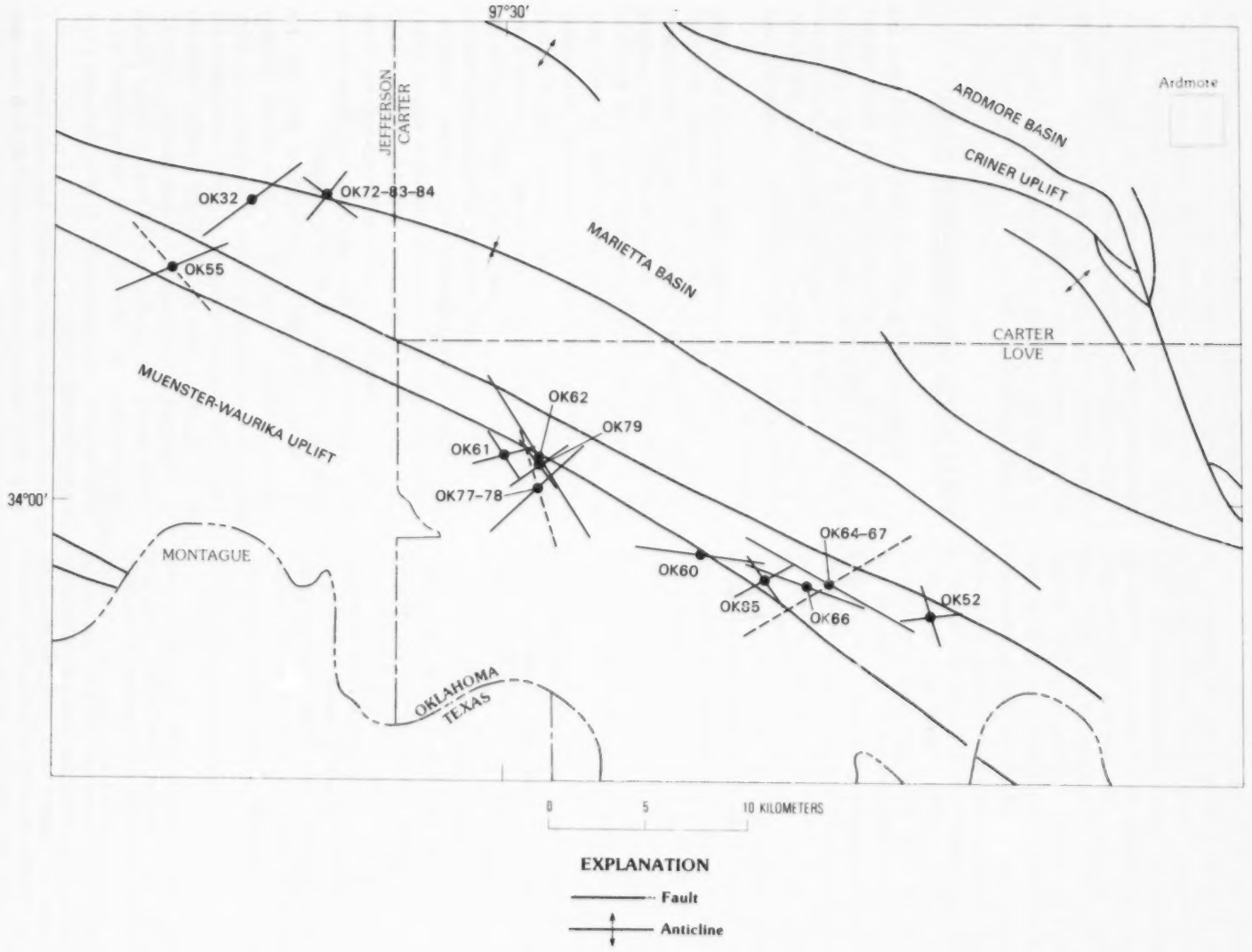


Figure 3. Structure map of the Marietta basin. Direction of wellbore enlargement indicated by dot with solid line; line length is proportional to statistical quality (A–C); for example, OK62 is B quality and OK32 is C quality. Bimodal-orthogonal data sets and data sets that are not bimodal but do have orthogonal data are indicated by paired solid lines and paired solid and dashed lines, respectively. Line lengths for some bimodal-orthogonal and orthogonal data sets are commonly shorter because of D-quality standard deviations. Structural features from Chenoweth (1972).

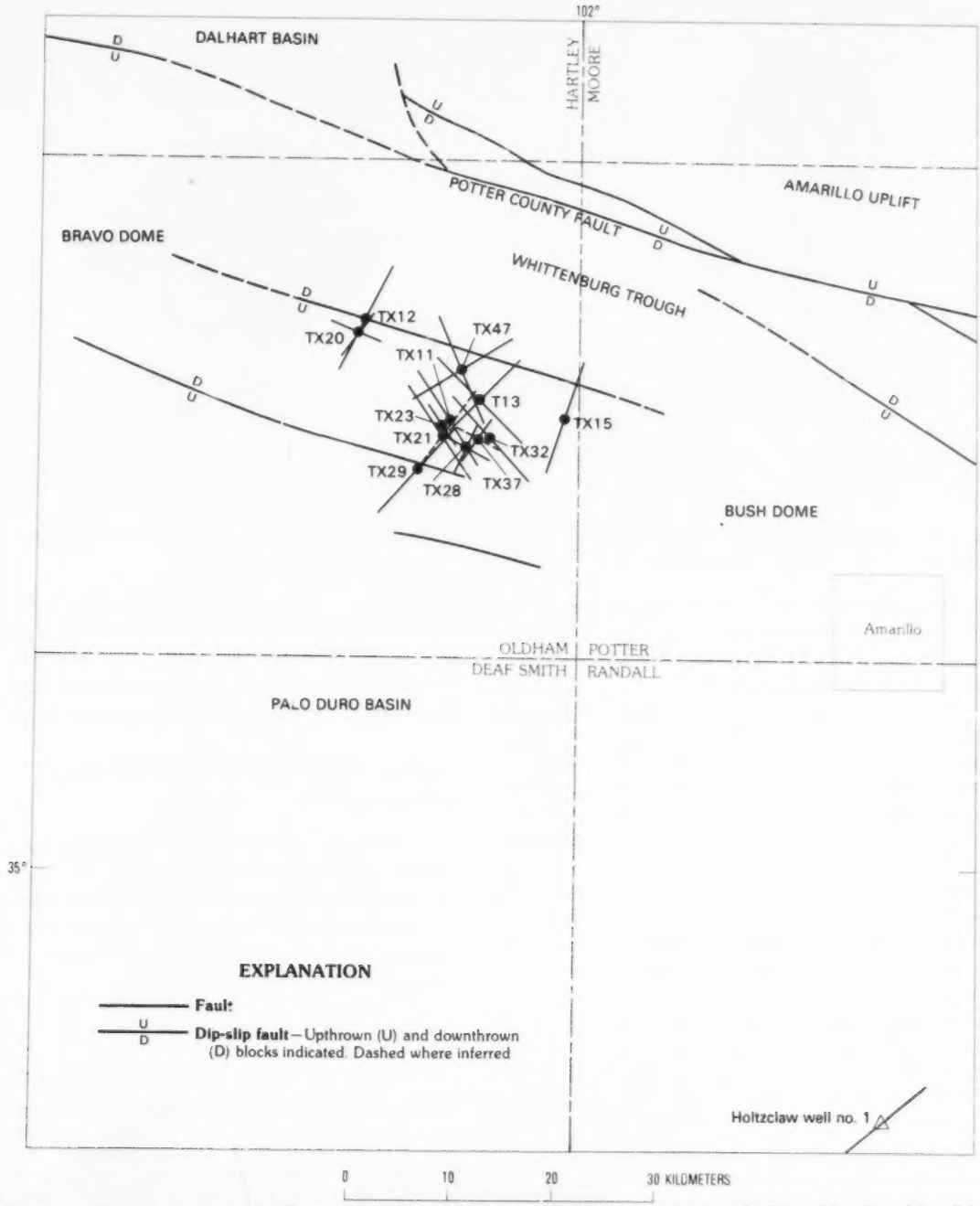


Figure 4. Structure map of the Bravo dome area. Direction of wellbore enlargement indicated by dot with solid line; line length is proportional to statistical quality (A–C); for example, TX12 is C quality. Bimodal-orthogonal data sets and data sets that are not bimodal but do have orthogonal data are indicated by paired solid lines and paired solid and dashed lines, respectively. Line lengths for some bimodal-orthogonal and orthogonal data sets commonly are shorter because of D-quality standard deviations. Open triangle with line indicates hydraulic fracturing data (von Schonfeldt and others, 1973). Structural features from McGookey and Goldstein (1982).

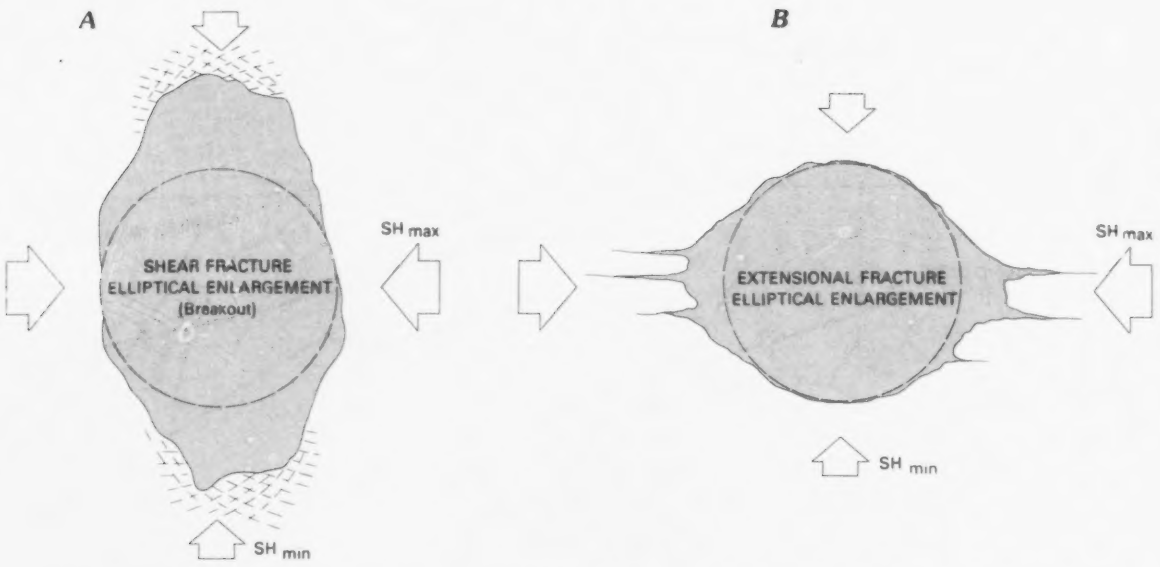


Figure 5. Cross sectional schematics of wellbores showing original borehole shape (dashed line) and enlarged borehole shape (solid line). Breakout (*A*) and fracture (*B*) elliptical wellbore enlargements are shown.

orthogonal data sets were used in the statistical calculations of study-area data composites (figs. 6–8, tables 2–4). Well locations and calculated mean orientations of the data are plotted in figures 2-4.

Plotted data (figs. 2–4) for individual well data sets consist of four or more wellbore enlargement orientations. Bimodal-orthogonal data sets have orthogonal modes of relatively equal numbers of wellbore enlargement orientations, whereas orthogonal data sets generally have only one wellbore enlargement orientation orthogonal to a preferred (primary) mode of the data. For bimodal-orthogonal data sets, the mean orientations of both modes are plotted as solid lines (figs. 2–4). Preferred modes and orthogonal trends in orthogonal data sets are plotted as solid and dashed lines, respectively.

Breakout data from the 16 well data sets in the eastern Anadarko basin study area form a consistent north-northwest trend. There are no bimodal data sets, and only three of the data sets have minor orthogonal east-northeast trends (fig. 2, table 2). Stress-related fracture wellbore enlargements rarely occur in the eastern Anadarko basin study area.

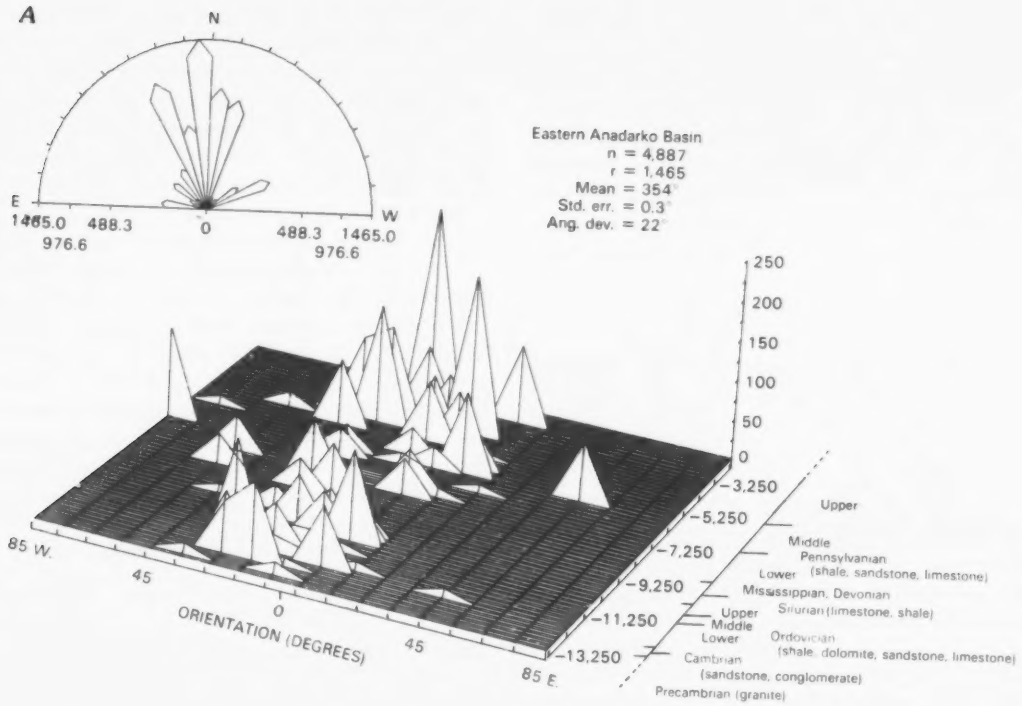
Common in the Marietta basin and the Bravo dome area are bimodal-orthogonal and orthogonal data sets and well data sets consisting entirely of inferred fracture wellbore enlargements (figs. 3 and 4). In the Marietta basin, 1 of the 12 well data sets consists exclusively of northwest-oriented breakout data, 5 data sets are composed of east-northeast to northeast-oriented inferred fracture enlargements, 6 data sets are bimodal-orthogonal, and 3 data sets are orthogonal by definition (table 3). A similar situation was observed in data for the Bravo dome area where of the 12 data sets 3 consist exclusively of breakout data, 3 consist exclusively of inferred fracture wellbore enlargements, 4 are bimodal-orthogonal, and 2 are orthogonal by definition.

ROCK TYPES OF ENLARGEMENT FORMATION

Probably because of the predominance of carbonate and shale rocks throughout the study region (American Association of Petroleum Geologists, 1983a, b), both breakouts and fracture enlargements are most common in limestone, dolomite, and shale rock units (tables 5 and 6, fig. 9).

In the eastern Anadarko basin, 62 percent of the breakouts and 80 percent of the fracture wellbore

Figure 6 (facing page). Three-dimensional histograms and frequency rose diagrams for the eastern Anadarko basin. Distributions of wellbore enlargements are shown with azimuth (*A*) versus depth (subsea) and (*B*) versus frequency of occurrence (feet or number). See text for explanation of statistical values shown. Depths in 1,000-ft increments. Approximate stratigraphic contacts: Upper and Middle Pennsylvanian at 5,500 ft; Middle and Lower Pennsylvanian at 7,000 ft; Lower Pennsylvanian and top of Mississippian, Devonian, and Silurian at 9,000 ft; base of Mississippian, Devonian, Silurian, and Upper Ordovician at 10,200 ft; Upper and Middle Ordovician at 10,700 ft; Middle and Lower Ordovician at 11,200 ft; Lower Ordovician and top of Cambrian at 12,500 ft; base of Cambrian and top of Precambrian at 13,000 ft.


A
N
E
W
1465.0 488.3 0 488.3 1465.0
976.6 976.6
Eastern Anadarko Basin
n = 4,887
r = 1,465
Mean = 354°
Std. err. = 0.3°
Ang. dev. = 22°
250
200
150
100
50
0
-3,250
-5,250
-7,250
-9,250
-11,250
-13,250
Upper
Middle
Pennsylvanian
Lower (shale, sandstone, limestone)
Mississippian, Devonian
Upper Silurian (limestone, shale)
Middle
Lower Ordovician
Cambrian (shale, dolomite, sandstone, limestone)
(sandstone, conglomerate)
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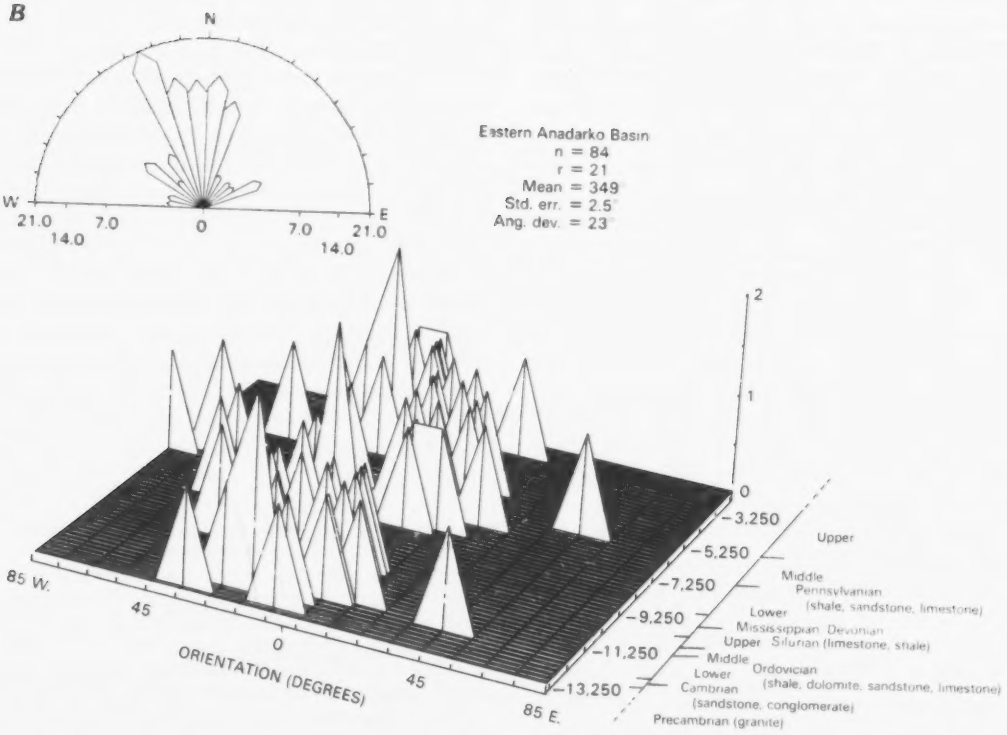
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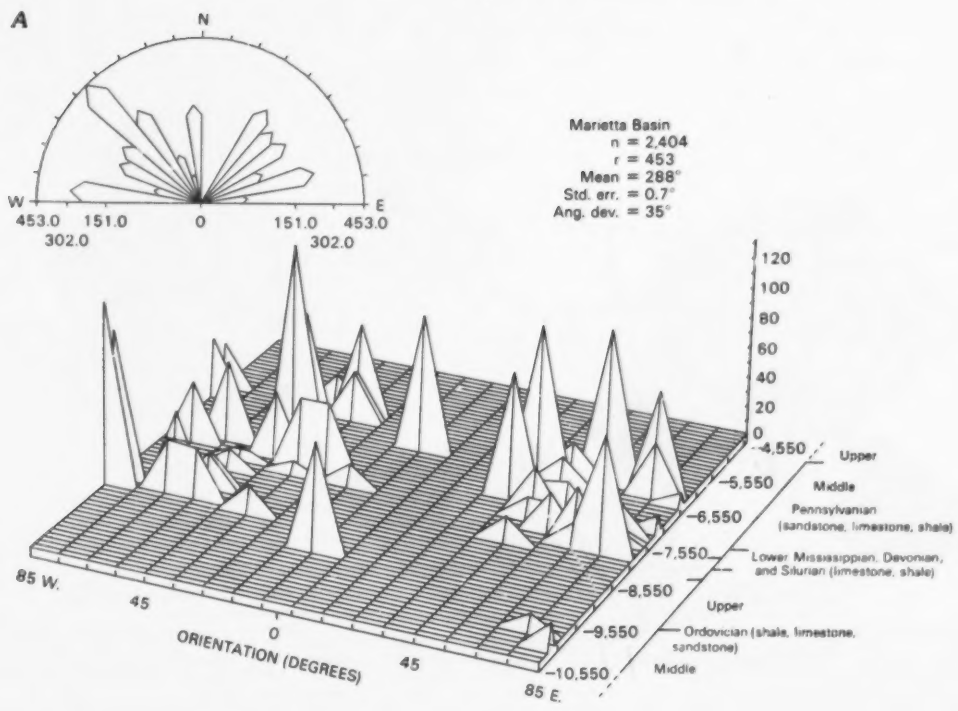
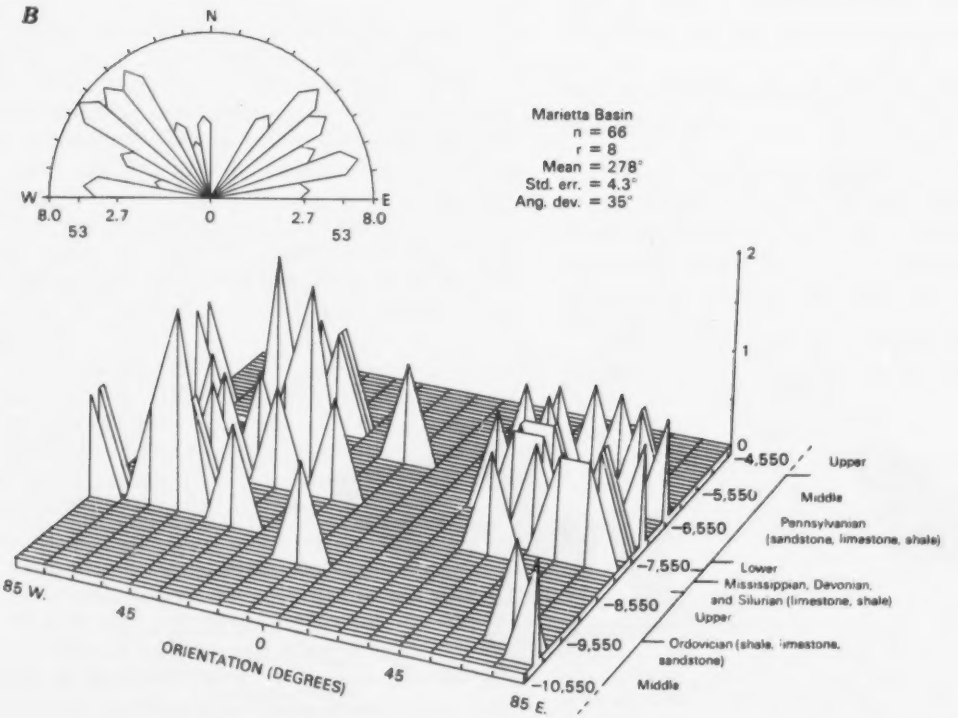
W
E
21.0 14.0 7.0 0 7.0 14.0 21.0
Eastern Anadarko Basin
n = 84
r = 21
Mean = 349°
Std. err. = 2.5°
Ang. dev. = 23°
2
1
0
-3,250
-5,250
-7,250
-9,250
-11,250
-13,250
Upper
Middle
Pennsylvanian
Lower (shale, sandstone, limestone)
Mississippian, Devonian
Upper Silurian (limestone, shale)
Middle
Lower Ordovician
Cambrian (shale, dolomite, sandstone, limestone)
(sandstone, conglomerate)
Precambrian (granite)
85 W.
45
0
45
85 E.
ORIENTATION (DEGREES)





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enlargements are in limestone (fig. 9). In the Marietta basin, an equal percentage (43) of both breakout and fracture wellbore enlargements are in limestone (fig. 9). Thirty percent of the breakouts are in formations of sandstone, shale, and limestone, and 27 percent of the fracture enlargements are in shale. In the Bravo dome area, 49 percent of the breakouts and 34 percent of the fracture wellbore enlargements are in dolomite, whereas 35 percent of the breakouts and 43 percent of the fracture enlargements are in shale (fig. 9).

The formation of stress-induced breakouts and stress-related fracture wellbore enlargements in particular rock types are less likely a function of rock type and more probably a function of the abundance of carbonate and shale rocks in the stratigraphic section represented in the dipmeter log records analyzed and the existing in situ stresses within the areas studied. That is, stress conditions necessary to initiate stress-induced and stress-related wellbore enlargement development probably are present within the dominant sedimentary rock types logged.

FRACTURE ENLARGEMENTS AND DATA SCATTER

Orthogonal trends in bimodal data sets associated with breakout and fracture-related wellbore enlargement orientations contribute significantly to increased standard deviations for individual well data sets and to the dispersion (data scatter) in data composites for the Marietta basin and Bravo dome study areas (figs. 6–8).

In this study, breakout and fracture-related wellbore enlargements were differentiated by comparing their enlargement orientations with known directions of SH_{max} from hydraulic-fracturing measurements (figs. 2 and 4, table 7). The data suggest that north-northwest to northwest-oriented wellbore enlargements are breakouts and that northeast-oriented wellbore enlargements are fracture-related wellbore enlargements.

Comparison of conductivity values associated with the cross sectional long and short wellbore enlargement axes (short/long axis conductivity ratios) has been suggested as a possible method of distinguishing breakout from fracture-related wellbore enlargements (Blümling, 1986). This method should work well only when the formation in which the enlargement has formed is of low porosity; that is, favorably oriented preexisting vertical fractures or drilling-induced hydraulic fractures associated with fracture wellbore enlargements may create a more direct path for induced current and thus higher conductivity values (D.G. Davis, oral commun., 1988) than the current path associated with the curvilinear shear failure of breakout wellbore enlargement formation (Dart and Zoback, 1989). In highly fractured or porous rock, dispersion of a directed current should result in lower conductivity values and thus make differentiation of wellbore enlargement type difficult. Detailed information concerning the rock type and porosity of the units in which wellbore enlargements formed is necessary to more accurately differentiate wellbore enlargement type. Greater accuracy in distinguishing between types of wellbore enlargements may be achieved, however, by using digitized dipmeter well logs, which should afford the analyst a greater sampling frequency of conductivity data.

In the areas studied, fracture and joint patterns observed at the surface and at depth agree with orientation trends observed in wellbore enlargement data. A study of subsurface fractures in the "Mississippi Lime" (driller's term) and the Devonian and Silurian Hunton Limestone (9,055–9,331 ft below ground surface) of Kingfisher County in the eastern Anadarko basin (fig. 2) reveals a bimodal pattern of vertical natural fractures (Brevetti and others, 1984): a primary north-south trend and a secondary east-west trend. These fractures are within the depth interval for breakout occurrence. The mean orientations of both fracture trends are subparallel with the mean orientations of breakouts and with the minor set of orthogonally oriented wellbore enlargements inferred to be fracture related.

In the Slick Hills area of Oklahoma, adjacent to and north of the Meers fault in the southwest corner of the eastern Anadarko basin (fig. 2) and approximately 70 km northwest of the Marietta basin, Wilhelm and Morgan (1986) observed a bimodal pattern of geographic lineaments oriented between N. 30°–60° W. and N. 40°–50° E. These "well-constrained" lineament patterns are interpreted as being associated with northwest-striking left-lateral and high-angle thrust faults and northeast-striking right-lateral faults (Wilhelm and Morgan, 1986). This bimodal pattern agrees with the mean orientations of breakouts and orthogonally oriented, inferred fracture-related wellbore enlargements from wells in the Marietta basin (fig. 3).

In the Bravo dome area of the Texas Panhandle (fig. 4), surface and subsurface fractures also form bimodal trends oriented roughly west-northwest and

Figure 7 (facing page). Three-dimensional histogram and frequency rose diagrams for the Marietta basin. Distributions of wellbore enlargements are shown with azimuth (*A*) versus depth (subsea) and (*B*) versus frequency of occurrence (feet or number). See text for explanation of statistical values shown. Depths are in 500-ft increments. Approximate stratigraphic contacts: Upper and Middle Pennsylvanian at 5,000 ft; Middle and Lower Pennsylvanian at 7,500 ft; Lower Pennsylvanian and top of Mississippian, Devonian, and Silurian at 7,700 ft; base of Mississippian, Devonian, Silurian, and Upper Ordovician at 8,300 ft; Upper and Middle Ordovician at 9,000 ft.

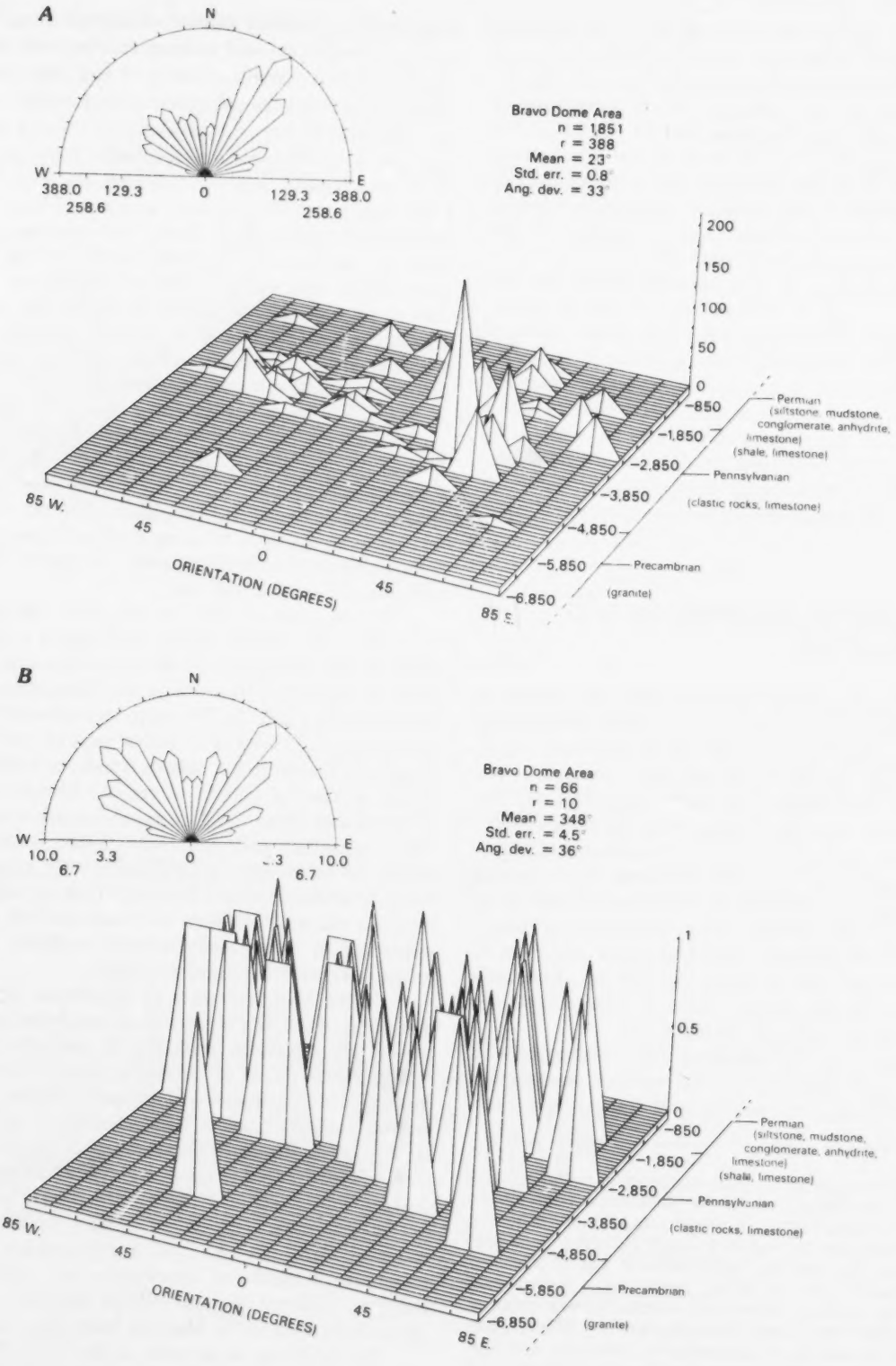

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Table 1. Quality criteria for breakout (wellbore enlargement) data

[A breakout data set is considered very poor (VP) if its standard deviation is greater than 30°, regardless of the number of breakouts measured. Leaders (--) indicate any number of breakouts. Table from M.L. Zoback (written commun., 1987)]

Data set quality	Number of breakouts	Angular deviation
A	≥10	≤12°
B	≥6	>12°, ≤20°
C	≥4	>20°, ≤25°
D	<4	>25°, ≤30°
VP	---	>30°

northeast (Gustavson and Budnik, 1985; Gustavson and Finley, 1985). Although the bimodal trends of these fractures are somewhat random, agreement does exist between the bimodal trends of subsurface near-vertical fractures (Gustavson and Budnik, 1985) observed in the Stone and Webster Holtzclaw No. 1 well (fig. 4) and northwest- and northeast-oriented wellbore enlargements in the Bravo dome area.

In all three study areas, the mean orientations of breakouts and inferred fracture wellbore enlargements are about the same as bimodal orientations of observed natural fractures within or adjacent to these areas. This finding tends to support a genetic relationship between the formation of some wellbore enlargements and preexisting vertical fractures.

Studies show that drilling-induced hydraulic fracturing is related to an increase in hydrostatic pressure within the wellbore or to a decrease in rock tensile strength (Ellis and Swolfs, 1983; Stock and others, 1985). Unfortunately, an association between hydraulic fracturing and the formation of inferred fracture wellbore enlargements could not be verified for the study areas due to the unavailability of detailed drilling records of pumping pressures and fluid weights; however, changes in relative conductivity on dipmeter logs do show the coincidence of wellbore enlargements and formational or bedding boundaries.

A possible mechanism for the development of fracture-related enlargements of either type involves the "chipping out" of the wellbore during the drilling process (D.G. Davis, oral commun., 1988). By this means, the wellbore is enlarged elliptically in an area weakened by drilling-induced hydraulic fractures or by favorably oriented, open, preexisting vertical natural fractures or joint sets intersecting the borehole. The process of fracture-related enlargement formation may be aided by the erosional effects of circulating drilling fluid and drill-string wear.

Due to the difference in horizontal stress concentrations about the borehole, favorably oriented preexisting vertical fractures intersecting the wellbore should remain open and thus increase the possibility of mechanical wellbore enlargement. A possible example of this process is given by Gustavson and Budnik (1985) in their discussion of the preferred northeast orientation of fracture-related solution features in the Permian salt-bearing stratigraphy of the Texas Panhandle and northeast-oriented hydraulic fractures induced in the Stone and Webster Holtzclaw No. 1 well (fig. 4). Gustavson and Budnik postulated that dissolution of salt-bearing formations was more rapid in the direction of SH_{max} along northeast-oriented fractures.

Fractures intersecting the wellbore do not always develop wellbore enlargements. Eighty-four fractures observed as conductive anomalies on fracture identification logs from six Marietta basin wells (The Anchutz Corporation, unpub. data, 1987) exhibit very few wellbore enlargements. These 84 fractures, having a mean azimuth of N. 42° E. and primarily in the Upper Ordovician Viola Limestone, were compared with 35 northeast-oriented wellbore enlargements from 13 additional wells in the same basin. Many of the 35 northeast-oriented wellbore enlargements, inferred to be fracture related, are in limestone and shale formations and are associated with fracture-conductivity anomalies. These 35 wellbore enlargements have an average orientation of N. 65° E. The 27° difference in orientation between these two groups of data may be due in part to variations in natural fracture orientation, spacing, and dip or to the variation between present-day and paleostress orientations.

Preexisting fractures intersecting the borehole at azimuths parallel or subparallel with the SH_{min} direction may also contribute to development of stress-induced breakouts. This appears to be the case for at least one wellbore enlargement in the eastern Anadarko basin, well OK16 (fig. 2). This wellbore enlargement is associated with a conductivity anomaly indicative of fracturing but is oriented in the direction inferred for breakouts. This situation is not interpreted to be a 90° rotation of the stress field but rather the formation of a stress-induced breakout within an interval of the wellbore weakened by preexisting northwest-oriented vertical fracturing or jointing.

An increase in the difference in horizontal stress magnitudes associated with gravitational loading, rock properties, and bedding thickness (Amadei and others, 1988) may also contribute to the formation of fracture

Figure 8 (facing page). Three-dimensional histogram and frequency rose diagrams for the Bravo dome area. Distributions of wellbore enlargements are shown with azimuth (*A*) versus depth (subsea) and (*B*) versus frequency of occurrence (feet or number). Clastic rocks are granite wash. See text for explanation of statistical values shown. Depths are in 500-ft increments. Approximate stratigraphic contacts: Permian and Pennsylvanian at 1,700 ft; Pennsylvanian and Precambrian at 5,000 ft.

Table 2. Wellbore enlargement data for the eastern Anadarko basin

[Latitude and longitude are degrees north and west, respectively. Well depth is feet below sea level; ground level is elevation in feet; logged and data intervals are in feet. Columns for feet and number are totals of vertical feet and number of individual wellbore enlargements. Log quality: G, good; VG, very good; F, fair; P, poor. See table 1 for explanation of statistical quality]

Well index number	County	Latitude	Longitude	Ground level	Well depth	Logged interval	Data interval	Feet	Number	Quality		Standard error	Angular deviation	SH_{min}
										Log	Statistical			
OK4	Grady	34.887	97.737	1,064	13,273	11,192-13,219	11,192-13,205	170	4	G	C	8.5	17	344
OK5	Grady	34.930	97.668	1,155	13,990	8,824-13,374	11,658-12,666	45	4	F	C	4.8	10	344
OK9	Canadian	35.485	97.906	1,342	12,546	10,036-12,536	10,086-14,035	38	4	VG	C	10.8	22	350
OK11	McClain	35.141	97.585	1,210	9,891	5,778-9,871	6,811-8,541	389	8	G	C	7.6	22	328
OK15*	Grady	34.985	97.739	1,070	13,073	10,415-13,031	11,641-12,803	232	5	F	C	.3	4	340
OK16	Grady	35.216	97.881	1,242	12,204	10,544-12,154	10,990-11,861	135	4	G	C	7.0	14	327
OK17*	McClain	34.928	97.337	1,115	7,894	5,813-7,863	5,847-6,673	169	4	G	D	6.7	12	341
OK18	Grady	34.872	97.667	1,003	12,408	9,278-12,398	10,078-11,898	189	4	F	C	1.1	2	339
OK22*	Grady	34.729	97.732	1,229	10,059	3,649-10,059	3,991-6,318	525	9	G	B	.3	7	5
OK27	Kingfisher	35.749	97.910	1,091	8,771	6,091-8,795	6,091-8,217	225	6	VG	B	7.5	6	14
OK36	Logan	35.905	97.146	902	4,185	2,161-4,100	2,446-3,911	437	7	G	B	4.8	13	346
OK38	Cleveland	35.346	97.182	1,205	5,073	3,033-5,521	3,133-5,286	229	4	P	C	8.5	17	334
OK40	Cleveland	35.319	97.246	1,086	5,522	3,521-5,521	3,762-5,186	375	4	F	C	5.2	10	338
OK100	Comanche	34.725	98.240	1,206	8,978	1,182-6,831	3,202-6,727	579	5	F	C	10.4	23	34
OK102-108*	Canadian	35.659	97.731	1,250	6,904	4,934-6,902	5,084-6,707	793	5	P-G	D	5.4	1	358
OK105	Canadian	36.530	99.052	1,394	11,491	9,491-11,488	10,223-11,362	357	7	G	B	3	7	2
Composite of study area data								4,887	84		2.1	18	348	

*The distribution of directional data was bimodal with orthogonally oriented trends of unequal population size.

Table 3. Wellbore enlargement data for the Marietta basin

[Latitude and longitude are degrees north and west, respectively. Well depth is feet below sea level; ground level is elevation in feet; logged and data intervals are in feet. Columns for feet and number are totals of vertical feet and number of individual wellbore enlargements. Log quality: G, good; F, fair; P, poor. See table 1 for explanation of statistical quality]

Well index number	County	Latitude	Longitude	Ground level	Well depth	Logged interval	Data interval	Feet	Number	Quality		Standard error	Angular deviation	SH_{min}
										Log	Statistical			
OK32	Jefferson	34.135	97.626	816	6,871	4,471-6,464	5,987-6,592	216	4	G	C	9.9	20	324
OK55[1]	Jefferson	33.103	97.675	793	9,934	5,407-6,527	5,726-6,446	152	5	F	C	5.6	11	337
OK52[2]	Love	33.949	97.266	918	10,547	8,911-10,516	8,939-10,211	116	4	F	D	8.8	12	341
OK60	Love	33.976	97.387	930	8,123	5,054-8,100	5,776-7,908	115	4	P	C	10.1	20	278
OK61[2]	Love	34.023	97.492	855	8,028	6,028-9,771	7,214-7,894	106	6	G	D	7.0	10	328
OK62	Love	34.022	97.476	840	7,708	5,590-7,799	5,818-7,619	421	10	G	B	5.5	18	323
OK64-67[1]	Love	33.963	97.320	785	9,123	6,900-9,126	6,228-8,776	286	7	G-F	B	0.8	12	289
OK66	Love	33.956	97.331	845	8,799	6,739-8,798	8,337-8,635	162	4	P	C	5.7	11	289
OK72-83-84[2]	Jefferson	34.137	97.595	839	7,999	5,789-7,998	7,049-7,798	312	5	F-F	D	1.4	2	310
OK77-78[1]	Love	34.004	97.474	913	7,819	5,774-7,796	7,072-7,698	163	6	F-G	C	8.9	22	343
OK79[2]	Love	34.022	97.476	876	7,760	5,708-7,745	6,508-7,654	173	5	G	D	3.5	5	323
OK85[2]	Love	33.960	97.352	954	8,399	6,333-8,383	6,833-8,189	151	4	F	D	3.5	5	323
Composite of study area data								2,373	64			3.3	20	311

[1]The distribution of directional data was bimodal with orthogonally oriented trends of unequal population size.

[2]The distribution of data was bimodal with orthogonally oriented trends of approximately equal population size.

Table 4. Wellbore enlargement data for the Bravo dome area

[Latitude and longitude are degrees north and west, respectively. Well depth is feet below sea level; ground level is elevation in feet; logged and data intervals are in feet. Columns for feet and number are totals of vertical feet and number of individual wellbore enlargements. Log quality: G, good; F, fair; P, poor. See table 1 for explanation of statistical quality]

Well index number	County	Latitude	Longitude	Ground level	Well depth	Logged interval	Data interval	Feet	Number	Quality		Standard error	Angular deviation	SH_{min}
										Log	Statistical			
TX11	Oldham	35.370	102.306	4,020	4,202	2,192-4,198	2,322-3,244	184	8	G	C	8.8	25	328
TX12	Oldham	35.465	102.372	3,279	4,857	2,861-4,864	3,446-4,393	360	7	F	C	8.1	22	27
TX13[1]	Oldham	35.379	102.260	3,615	4,475	2,469-4,469	2,788-3,655	229	7	F	C	2.1	4	314
TX15	Oldham	35.390	102.163	3,257	2,781	1,438-2,779	2,291-2,611	166	4	G	C	10	19	19
TX20[1]	Oldham	35.443	102.379	3,500	4,757	2,740-4,747	3,110-3,747	85	4	G	D	1.8	2	293
TX21[2]	Oldham	35.355	102.301	3,706	3,733	2,833-3,583	3,031-3,305	95	4	F	C	.9	8	327
TX23	Oldham	35.388	102.331	3,715	4,076	2,075-4,075	2,340-3,157	55	4	G	C	5.9	12	326
TX28[1]	Oldham	35.328	102.368	3,575	4,064	1,965-4,063	2,428-4,019	128	6	F	D	3.6	6	302
TX29	Oldham	35.297	102.335	3,542	3,235	1,232-3,232	1,233-1,744	128	4	F	C	12	23	37
TX32	Oldham	35.371	102.213	3,539	3,750	1,650-3,739	2,453-3,100	53	4	F	C	9.4	19	317
TX37[2]	Oldham	35.366	102.237	3,590	3,596	400-3,618	826-2,786	129	4	F	D	3.9	1	300
TX47[1]	Oldham	35.404	102.330	3,451	6,887	837-6,839	1,227-5,691	239	10	G	C	3.8	9	336
Composite of study area data								1,851	66			2.9	17	319

[1]The distribution of data was bimodal with orthogonally oriented trends of approximately equal population size.

[2]The distribution of directional data was bimodal with orthogonally oriented trends of unequal population size.

wellbore enlargements in the study areas . Amadei and others proposed a model of gravity-induced variation in stress magnitudes in anisotropic, stratified rock masses by treating layered strata as finite mechanical units. This model predicts that induced components of horizontal stress can vary in magnitude between rock units, either less or more than the vertical stress.

Formation of randomly oriented wellbore enlargements associated with lower confining pressures at shallow depths (Dart, 1987; Springer, 1987) can generally be ruled out as a contributor to data scatter because near-surface (< 1,000 ft subsea) wellbore enlargements are commonly washed out and enlarged in both orthogonal directions. These data were not considered reliable and were not used.

Small differences in horizontal-stress magnitudes (Springer, 1987), as measured in the Stone and Webster Holtzclaw No. 1 well (fig. 4), may contribute to dispersion among enlargement orientations in the Bravo dome area. This cannot be said, however, for the eastern Anadarko and Marietta basins because in situ measurements of horizontal stress magnitudes are not available.

The observed randomness in wellbore enlargement orientations in the Marietta basin and Bravo dome areas is not thought to be related to a large horizontal stress ratio and variation in borehole shape (Morin and others, in press). Large horizontal stress differences were not observed in the Stone and Webster Holtzclaw No. 1 well (Stone and Webster Engineering Corporation, 1983), and the aseismicity of the study region (fig. 1) (Stone and Webster Engineering Corporation, 1983) suggests a small difference in regional horizontal stresses.

INFERRED STRESS DIRECTIONS AND RELATIVE STRESS MAGNITUDES

Directions of SH_{max} calculated from stress measurements (table 7) agree with directions of SH_{max} inferred from breakout data (table 8) in the study region. The average direction of SH_{max} inferred from hydraulic-fracturing measurements for the region (fig. 1) is N. 50° E., and the average direction of SH_{max} inferred from breakout data for the three study areas is N. 56° E.

The relative magnitudes of S_1, S_2, and S_3 within the study region can be evaluated from available hydraulic-fracturing data, evidence of recent faulting, and the frequency of breakout occurrence with depth. Values of S_V SH_{min}, and SH_{max} magnitudes from hydraulic-fracturing measurements exist for one well (Stone and Webster Holtzclaw No. 1) within the study region (fig. 2, table 7). The relationship of principal stress magnitudes from the Stone and Webster Holtzclaw well No. 1 (fig. 4), located 80 km southeast of the Bravo dome area in the Palo Duro basin, is

$$S_1 > S_2 > S_3, \text{ or } S_v > SH_{max} > SH_{min}, \text{ or } S_v > S_{NE} > S_{NW}.$$

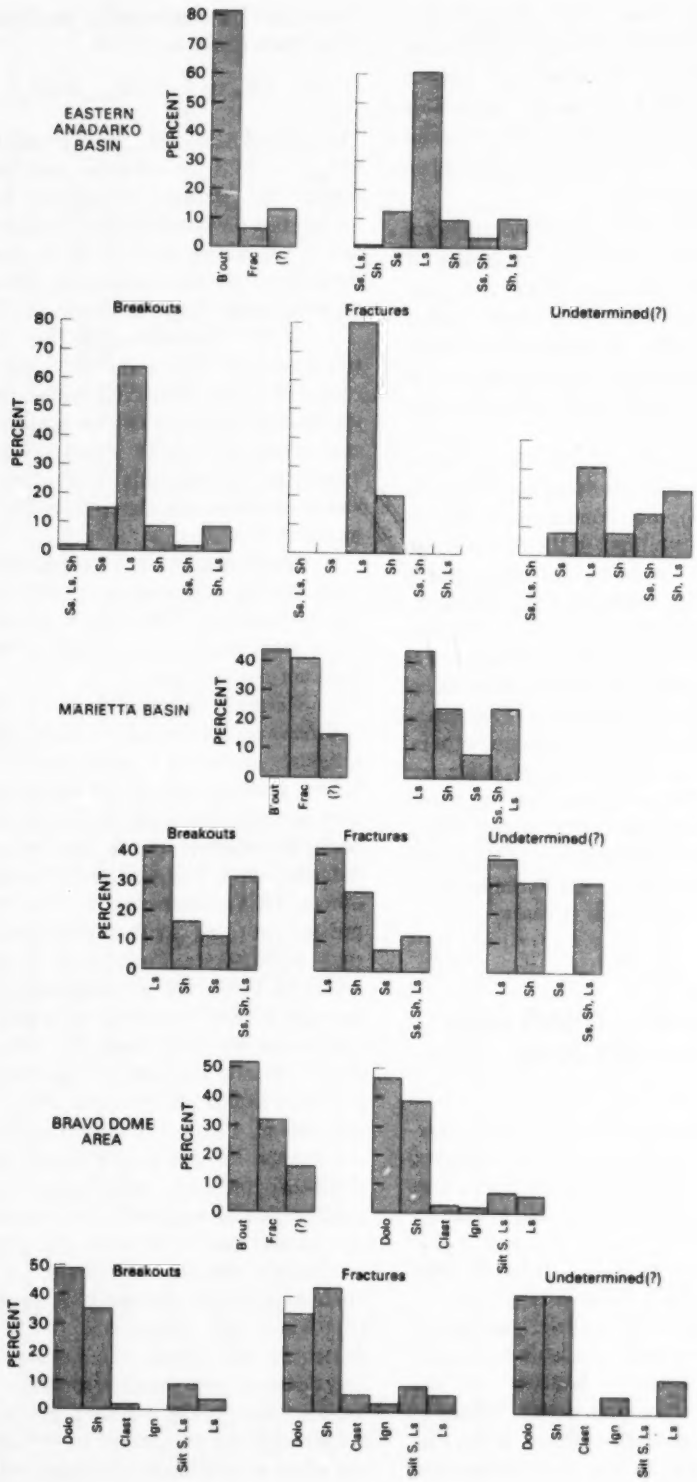
The ratio of S_V to SH_{max} is 1.19 and the ratio of SH_{max} to SH_{min} is 1.28 for siltstone and limestone formations (table 7). Stresses measured for intervening salt formations deviate from this stress relationship. Because salt is an elastoplastic rock, stresses measured in salt formations are not considered reliable indicators of the regional stress field (Borjeson and Lamb, 1988).

In the Arbuckle uplift (fig. 1), surface overcoring stress measurements (table 7) are an unreliable indication of stress conditions within the region because of the domed structure of this igneous body (H.S. Swolfs, oral commun., 1988). Breakout stress data from the vicinity of the Arbuckle uplift agree only generally with stress directions calculated from the overcoring measurements in this area.

Stress-magnitude calculations using mini-frac (H.S. Swolfs, oral commun., 1988) and leak-off test data (Ervine and Bell, 1987) could not be made for the three study areas because these types of borehole pressure test data are not available.

Relative horizontal stress differences may be approximately inferred by examining the frequency of breakout occurrence with depth. Initiation of shear-failure spalling and rate of breakout development probably are controlled by the horizontal stress difference about the wellbore and the confining strength of the rock (Mastin, 1984; Haimson and Herrick, 1985; Zoback and others, 1985). Assuming that the fracture gradient, the pressure per unit depth required to fracture or cause the rock to separate (Society of Professional Well Log Analysts, 1984), and the magnitudes of S_1, S_2, and S_3 all increase at their respective rates with depth, the following conditions are likely true: (1) when breakouts do not occur or are random in orientation, $SH_{max} \simeq SH_{min}$; (2) when breakouts do occur, $SH_{max}/SH_{min} > 1$ (Zoback and others, 1985); (3) when the frequency of breakout occurrence increases with depth, the horizontal stress difference increases with depth (because the fracture gradient is also assumed to be increasing with depth but at a slower rate); (4) when the frequency of breakout occurrence remains about the same with depth, the horizontal stress difference is probably constant; and (5) when the frequency of breakout occurrence decreases with depth, the horizontal stress difference may decrease with depth or increase at a slower rate than the increase in the fracture gradient. Thus, breakout occurrence and the extent of breakout development in any given area is likely associated with the rates at which in situ stresses change with depth.

In a seismically active area where S_1 is horizontal, such as the New Madrid area of the Mississippi Embay-



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ment (Zoback and Zoback, 1980), stress-induced wellbore enlargements from two wells (Dart, 1987) appear to be of greater vertical length (table 9) and have a distinct, characteristic shape (as seen on the dipmeter log). In contrast, in a relatively aseismic area such as the Palo Duro basin (Stone and Webster Corporation, 1983), where S_1 is vertical and where in the near surface S_2 may not be significantly greater than S_3 (table 7)(Borjeson and Lamb, 1987), wellbore enlargements in nearby wells (Bravo dome area), on average, appear to have shorter vertical lengths (table 9) and less well defined trace character on the dipmeter log (log quality on table 4). If wellbore enlargements are compared for areas having different levels of seismic activity but with similar sedimentary rock types, as is probably the case for the New Madrid seismic zone and the Bravo dome area, wellbore enlargement length and frequency of occurrence are likely a function of the horizontal stress difference.

Figures 6–8 illustrate the relationship of wellbore enlargement vertical length and frequency of occurrence to depth. For the eastern Anadarko basin data (fig. 6), frequency of breakout occurrence (number) does not decrease with depth for the logged interval (~3,000–~13,000 ft); however, breakout length does decrease with depth (fig. 6). This decrease is expected given the longer time period during which breakouts can develop in the upper part of the borehole and the subsequent longer exposure time to drill-string wear. Although the marked decrease in breakout occurrence between depths of about 6,000 and 9,000 ft (fig. 6) cannot be accounted for, it may be the result of an increase in rock tensile strength or a decrease in the ratio of horizontal stresses within this interval of Middle Pennsylvanian (Desmoinesian and Atokan) and Lower Pennsylvanian (Morrowan and Springeran) formations.

In the Marietta basin (fig. 7), both breakouts and fracture wellbore enlargements occur at approximately the same frequency with depth. The fact that they seem to terminate at about 9,000 ft may be related to the small number of wells (three) that were logged below this depth. In the Marietta basin data, scatter among breakout orientations contrasts with the tight grouping of northeast-oriented fracture-related wellbore enlargements. This contrast may be a function of the ratios of principal stresses in situ. A decrease in the ratio of horizontal stresses in the Marietta basin may contribute to scatter among breakout orientations, whereas an increase in the ratio of S_V to SH_{max} may contribute to drilling-induced hydraulic fracturing of the wellbore and the formation of fracture enlargements. In normal-faulting stress regimes where S_1 is vertical, drilling-induced hydraulic fracturing is more likely to occur than in compressive stress regimes where S_1 is horizontal (Healy and others, 1984; Stock and others, 1985).

Breakout and fracture wellbore enlargements occur with depth at approximately the same frequency (number) in the Bravo dome area data (fig. 8). Fracture enlargements have longer vertical lengths than breakouts and, as in the Marietta basin data, form a tighter grouping of northeast-oriented fracture-related wellbore enlargements than northwest-oriented breakout wellbore enlargements (fig. 8). Neither breakouts nor fracture-related wellbore enlargements occur below 5,750 ft. Only 1 of the 12 well data sets had a logged interval extending below this depth. In the logging interval above 5,750 ft, both breakout and fracture wellbore enlargement development decrease with depth. Very few wellbore enlargements of either type occur within the 1,500-ft interval between 4,250 and 7,500 ft (fig. 8). This apparent decrease in wellbore enlargement development below 4,250 ft may indicate changing stress ratios (S_V/SH_{max} and SH_{max}/SH_{min}) with depth. The tight grouping of well-developed fracture-related enlargements in the Bravo dome area data may indicate a normal-faulting stress regime. Hydraulic-fracturing measurements of S_1, S_2, and S_3 from the Stone and Webster Holtzclaw No. 1 well in the northern Palo Duro basin (fig. 4) confirm that this part of the Texas Panhandle (fig. 1) is a normal-faulting stress regime.

Several important observations can be made concerning the state of stress within the study region.

1. Strike-slip and reverse-fault movement on the Meers fault (fig. 2) and possible displacement on other west-northwest-oriented faults in the Frontal fault system of southern Oklahoma are inconsistent with a normal-faulting stress regime indicated for the Texas Panhandle.

2. Hydraulic-fracturing measurements in the Stone and Webster Holtzclaw No. 1 well (fig. 4, table 6) were made at shallow depths (1,854–2,794 ft below ground surface). The ratios of S_V/SH_{max} and SH_{max}/SH_{min} are close to 1.0. The difference in SH_{max} and SH_{min} magnitudes increases with depth, whereas the difference in S_V and SH_{max} magnitudes decreases with depth. The ratios of stresses may be different at depth than they are near the surface.

3. The Bravo dome and northern Palo Duro basin areas lie on or very near the boundary between the southern Great Plains and Midcontinent stress provinces. The states of stress for these two provinces are

Figure 9 (facing page). Vertical bar graphs of wellbore enlargement type and rock type of enlargement occurrence for the eastern Anadarko basin, Marietta basin, and Bravo dome study areas. Bars represent percentages of the total data set for each study area. Enlargement types: B'out, breakout; Frac, fracture; (?), undetermined. Rock types: Sh, shale; Ss, sandstone; Ls, limestone; Dolo, dolomite; Silt S, siltstone; Ign, igneous; Clast, clastic.

Table 5. Stratigraphic units logged

[Lithologic abbreviations: sandstone (SS), limestone (LS), shale (SH), dolomite (DOLO), conglomerate (CONG), and mudstone (MDS). Quotation marks (") denote informal usage of names, generally drillers' terms. Permian(?)=undifferentiated Wolfcampian-age clastic and limestone formations. Stratigraphic nomenclature follows usage of Jordan (1957), Bradfield (1968), Adler (1971), Preston and others (1982), McGookey and Goldstein (1982), American Association of Petroleum Geologists (1983a, b), and Petroleum Information Corporation well scout-cards of formation tops]

System	Series	Eastern Anadarko basin Lithologic unit	Marietta basin Lithologic unit	Bravo Dome area Lithologic unit
Permian	Leonardian			Clear Fork Group "Tubb sandstone" "Red Cave formation" (MDS) "Panhandle lime"
	Wolfcampian			"Brown dolomite" Permian(?), undifferentiated
	Virgilian	Pawhuska Formation (LS) "Endicott sand" "Lovell sand" "Tonkawa sand"		Cisco Group (SH)
	Missourian	Hoxbar Group Avant Limestone Member Dewey Limestone Hogshooter Limestone "Layton sand" "Checkerboard sand" "Cleveland sand" "Wade sand" Confederate Limestone Member	Hoxbar Group Daube Limestone Anadarche Limestone "Hewitt lignite" "Palacine shale" Confederate Limestone Member "Chubbee sand"	Canyon Group "Pennsylvanian shale" "Missourian shale" "Canyon granite wash" "upper granite wash" "massive granite wash" "granite wash"
	Desmoinesian			
Pennsylvanian (part)		Deese Group "Hart sand" "Big Lime" "Oswego lime" Cherokee Group "Prue sand" Verdigris Limestone "Skinner sand" "Pink lime" "Osborne sand" "Red Fork sand" Inola Limestone "Bartlesville sand" "Gibson sand"	Deese Group (LS,SS,SH) "Detrital zone" "Lower Deese" (coal) "Maroon shale" "Pennsylvanian sand" "Sanders" ("Lower Deese Group"?, SS,SH)	"Strawn limestone" "granite wash"
	Atokan	Atoka Formation (SH,LS) Novi Limestone		

Table 5. Continued

System	Series	Eastern Anadarko basin Lithologic unit	Marietta basin Lithologic unit	Bravo Dome area Lithologic unit
Pennsylvanian (part)	Morrowan	Dornick Hills Group Primrose Sandstone	Dornick Hills Group (SH,SS,LS,CONG)	
	Springerian	Springer Group (SH) "Upper Norton sandstone" "Cunningham sand" "Britt sandstone"	"Pennsylvanian detrital zone"	
Mississippian	Chesterian	Caney Shale "Chester limestone" "Manning zone" (LS,SH)		
	Meramecian	"Meramec limestone" "Mississippi limestone" Mayes Limestone Sycamore Limestone	Mayes Limestone Sycamore Limestone	
Devonian	Upper	Woodford Shale	Woodford Shale	
	Lower	"Misener sandstone" Hunton Group (LS) Bois d'Arc Limestone	Hunton Group (LS,SH)	
Silurian	Lower	Chimneyhill Limestone		
Ordovician	Upper	Sylvan Shale "Sylvan dolomite" Viola Limestone	Viola Limestone	
	Middle	Simpson Group Bromide Formation (SS,LS) Tulip Creek Formation (SS) McLish Formation (SS) Oil Creek Formation (DOLO,LS, SH, SS) Joins Formation (DOLO,LS)	Simpson Group Bromide Formation (LS,SS) McLish Formation Birdseye Limestone Member "Green shale" (Oil Creek? Formation)	
	Lower	Arbuckle Group (LS)		
Cambrian	Upper	Timbered Hills Group Reagan Sandstone (SH,CONG)		
Precambrian		Granite		Granite

Table 6. Wellbore enlargement type, frequency of occurrence, and orientation

[Azimuth (in degrees) is the median for every 10° interval between 90° W. and 90° E. Wellbore enlargement type and frequency are shown. Type: B, breakout; F, fracture; asterisk (*), uncertain. Frequency of occurrence is the number of discrete wellbore enlargement intervals. Quotation marks indicate informal usage of names. Permian (?) indicates undifferentiated Wolfcampian-age clastic and limestone formations]

Formation	Azimuth																		
	West									East									
	85	75	65	55	45	35	25	15	5	5	15	25	35	45	55	65	75	85
EASTERN ANADARKO BASIN																			
Avant Limestone Member							B2	B2			B1								
Hogshooter Limestone								B1	B1										
"Checkerboard sand"						B1	B3	B1	B1										
"Cleveland sand"									B1										
Confederate Limestone Member										B2									
Deese Group		F1	F1							B2	B1	B2							
"Hart sand"					B1														
"Big Lime"										B1									
"Prue sand"																F1			
"Osborne sand"									B1										
Atoka Formation										B1									
"Chester limestone"											B1								
"Mississippi limestone"												*1							
Hunton Group							B1			B1									
Bois d'Arc Limestone						B1	B2	B1											
Chimneyhill Limestone							B2												
Sylvan Shale				*1			B2			B1				F1	F1				
Viola Limestone				*1	B1		B4	B3	B3	B3	B1								
Bromide Formation							B3	B2		B1									
Tulip Creek Formation							B1		B1										
McLish Formation						B1			B1	B1									
Oil Creek Formation							B1	B2											
Arbuckle Group					B1		B1												
Reagan Sandstone										B1	B1								
MARIETTA BASIN																			
Confederate Limestone Member					B1														
Deese Group	*2				B3	B3			B1										
"Maroon shale"			B1	B1									F1		F1				
"Sanders"					B2				B1								F1		
Dornick Hills Group		*1		B1		B1	B1							F2	F2		F1		
Woodford Shale																			F1
Viola Limestone	*3		B2	B6	B2			B1					F2	F4	F1	F2	F2	F1	
Simpson Group					B1		B1								F1		F2	F1	
Bromide Formation						B1									F2				
Birdseye Limestone Member																F1			
Green shale (Oil Creek Formation)												F1							
BRAVO DOME AREA																			
"Panhandle lime"								B1											
"Brown dolomite"		*1	B1	B2	B5	B6	B3	B2	B3		*2	F1	F4	F3		F2	F1		
Permian (?)			B1	B2		B1													
Cisco Group											*1		F2	F2					
"Pennsylvanian shale			B2	B1	B1	B1				B1	*2		F1	F3	F1	F1			
"Missourian shale"								B1											
"Upper granite wash"					B1								F2						
Granite										B1		F1							

interpreted as being opposite (Zoback and Zoback, 1980). The southern Great Plains stress province is a region of extensional tectonics with $SH_{min} = S_{NNE}$, whereas the Midcontinent stress province is a region of compressional tectonics with $SH_{max} = S_{NE}$ (Zoback and Zoback, 1980). Therefore, near-surface stress conditions in the Bravo dome area may deviate from those farther east within the Midcontinent stress province.

4. In view of available hydraulic-fracturing data (table 7) and the apparent recent strike-slip and reverse movement on the Meers fault (Ramelli and others, 1987; Luza and others, 1987; Madole, 1988), a transitional stress regime is inferred for the study region, changing from normal faulting ($S_V > SH_{max} > SH_{min}$ or $S_V > S_{NE} > S_{NW}$) in the Texas Panhandle to strike-slip ($SH_{max} > S_V > SH_{min}$ or $S_{NE} > S_V > S_{NW}$) and reverse

Table 7. In situ stress data, south-central United States

[Study type: HF, hydraulic fracturing; OC, overcoring. Leaders (--) indicate no data available]

type	Location	Rock type	Depth (ft from ground surface)	S_v (psi)	SH_{min} (psi)	SH_{max} (psi)	SH_{max} (direction)
HF[1]	Kingfisher Co., Okla., eastern Anadarko basin.	--	--	--	--	--	N. 65° E.
OC[2]	Johnston Co., Okla., Arbuckle uplift.	Granite	4.5	0	519	1,075	N. 94° E.
HF[3]	Randall Co., Texas, Palo Duro basin	Siltstone	1,854	1,835	1,110	1,260	N. 30° E.
		Anhydrite	2,334	2,335	--	--	N. 40° E.
		Salt	2,434	2,780	2,915	--	N. 60° E.
		Salt	2,505	2,950	3,500	--	N. 60° E.
		Limestone	2,794	2,810	1,940	2,650	N. 45° E.

[1]From von Schonfeldt and others (1973).
[2]From Hooker and Johnson (1969).
[3]From Borjeson and Lamb (1987).

Table 8. Inferred stress directions from wellbore enlargement orientations

Location	Primary rock type in which enlargements occur	Enlargment depth interval (ft subsea) From	To	SH_{max} from breakout data	Azimuth of fracture enlargment
Eastern Anadarko basin	Limestone and shale	-2,446	-13,205	N. 78° E.	N. 51° E.
Marietta basin	Limestone and shale	-5,726	-10,499	N. 41° E.	N. 65° E.
Bravo dome area	Dolomite and shale	-924	-6,516	N. 49° E.	N. 37° E.

Table 9. Comparison of wellbore enlargement data from different stress regimes

[Number of wellbore enlargements is a total from all well-data sets, regardless of statistical quality]

Study area (stress regime)	Number of well-data sets	Total vertical feet logged	Number of wellbore enlargements	Vertical feet of wellbore enlargement	Number of wellbore enlargements per well-data set (avg.)	Vertical feet of wellbore enlargements per well-data set (avg.)	Average vertical length (ft) of wellbore enlargments	Average of wellbore enlargements 1,000 ft of borehole logged
Mississippi Embayment[1]	1	5,471	11	1,784	11.0	1,784	162	2.0
Eastern Anadarko basin[2]	14	40,637	82	3,700	5.9	264	45	2.0
Marietta basin[3]	16	35,971	88	2,851	5.5	178	32	2.5
Bravo dome area[4]	18	42,406	108	3,364	6.0	187	31	2.6

[1]Compressional stress regime.
[2]Compressional (?) stress regime.
[3]Extensional (?) stress regime.
[4]Extensional stress regime.

faulting ($SH_{max} > SH_{min} > S_V$ or $S_{NE} > S_{NW} > S_V$) in Oklahoma.

Given such a limited stress-magnitude data base (tables 7, 8), speculation on the relative magnitudes of vertical or horizontal stresses within the study region is problematic.

TRANSPRESSIONAL (OBLIQUE COMPRESSIONAL) STRESSES AND FAULT-BOUNDED BLOCKS

Many of the data sets from the Marietta basin and the Bravo dome area are bimodal (figs. 2–4, 7, 8, 10), whereas in the eastern Anadarko basin bimodal data sets of enlargement orientations are less common (figs. 2, 6, 10). The abundance of bimodal-orthogonal data sets in the Marietta basin and the Bravo dome area reflects the fracture history and suggests a local change in stress conditions related to mapped subparallel surface faults in the Marietta basin (fig. 3) and mapped subparallel basements faults in the Bravo dome area (fig. 4). Well locations in the eastern Anadarko basin (fig. 2) are distributed over a broad area and generally are not located between subparallel faults.

Preexisting fractures in an array of orientations may exist within blocks bounded by subparallel faults. The area between or above subparallel discontinuities likely has experienced an intense fracturing history

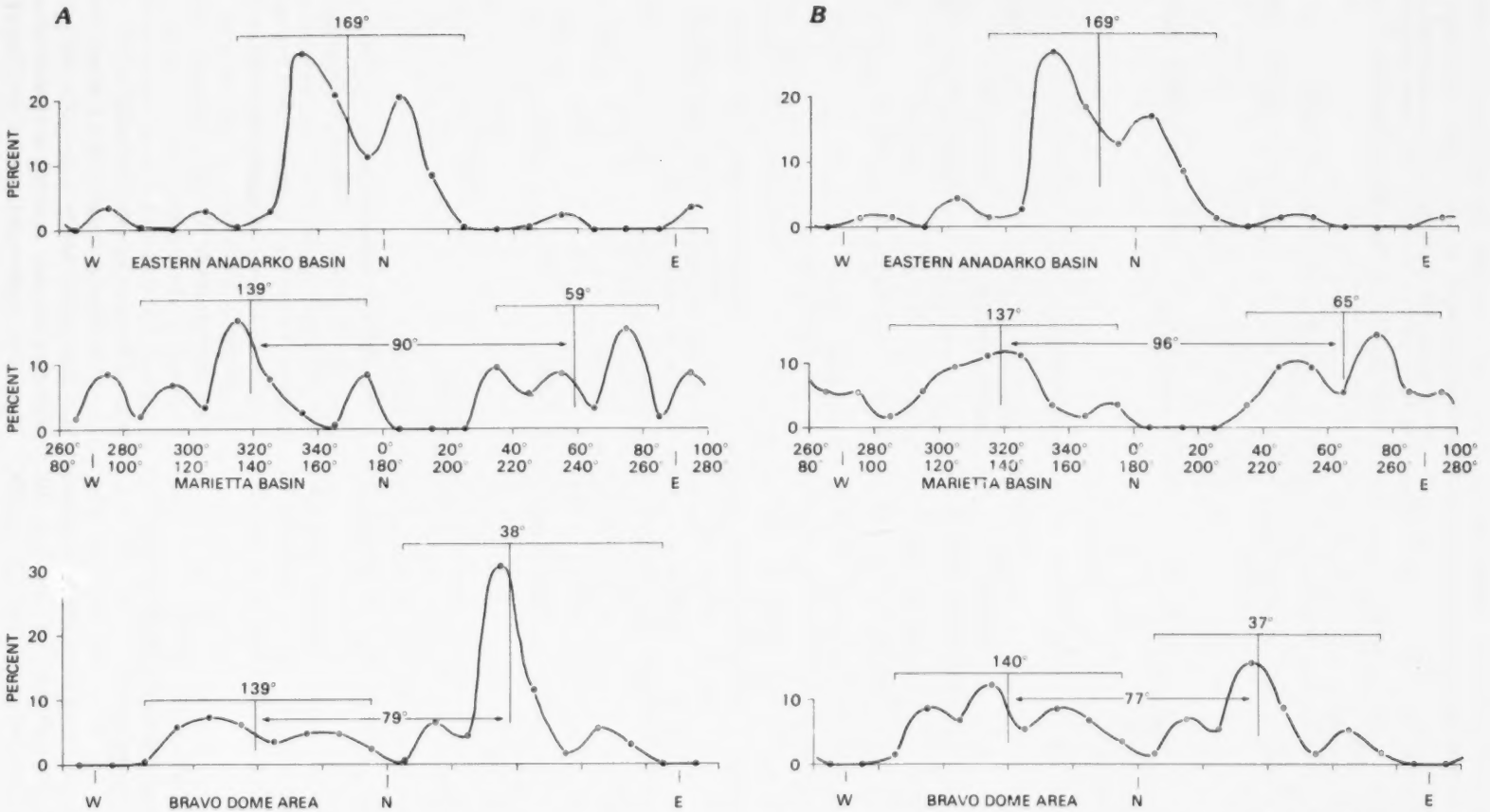

Figure 10. Histogram of wellbore enlargement data for the eastern Anadarko basin, Marietta basin, and Bravo dome study areas showing the bimodal-orthogonal distribution of enlargement orientations from the Marietta basin and the Bravo dome areas. Only data from wells with A-C statistical quality or with bimodal-orthogonal distribution were used (tables 1–4). Plots are a function of the percentage of the data used, either feet or number. Plot groups: *A*, Vertical feet of wellbore for a given azimuth; *B*, Cumulative number of individual wellbore enlargements for a given azimuth.

resulting in formation of sets of favorably oriented fractures or joints that would increase the likelihood of fracture-related wellbore enlargement development.

Where fracture-related enlargements have formed in response to drilling-induced hydraulic fracturing, an increase in the occurrence of fracture-related wellbore enlargements may reflect a local change in the regional stress field. Drilling-induced hydraulic fracturing is more likely to develop in a normal-faulting stress regime (Healy and others, 1984; Stock and others, 1985). An extensional (normal) faulting stress regime in the Marietta basin study area suggested by the occurrence of fracture wellbore enlargements may be a local stress anomaly in an otherwise compressional stress regime. Rogers (1984) and Hempton and Neher (1986) described structural settings in which extensional and compressional stresses develop between and near the ends of left-stepping and right-stepping en echelon strike-slip faults in response to regional horizontal compression oblique (transpressional) to their strike. Subparallel faults in the Marietta basin and Bravo dome area are not en echelon by definition; however, these two areas structurally resemble the areas described by Rogers (1984) and Hempton and Neher (1986). This similarity of structural settings and orientations of horizontal stresses suggests that extensional stress conditions (normal-faulting regime) may exist within blocks bounded by west-northwest-trending subparallel faults where SH_{max} is oblique to their strike.

A comparison of the calculated orientations of SH_{max} from breakout data (table 8) shows a 37° difference between the eastern Anadarko and Marietta basins and a 29° difference between the eastern Anadarko basin and the Bravo dome area. SH_{max} orientations calculated for the Marietta basin and the Bravo dome area differ by only 8°. The similarities of these two differences (37° and 29°) may correlate with the apparent similarities in structural settings of the Marietta basin and the Bravo dome area and with the possible local variation in horizontal stresses associated with the orientation of SH_{max} and west-northwest-trending subparallel faults.

CONCLUSIONS

From wellbore breakout data, SH_{max} is inferred to be N. 78° E. for the eastern Anadarko basin, N. 41° E. for the Marietta basin, and N. 49° E. for the Bravo dome area. Bimodal sets of wellbore enlargement data are interpreted as consisting of a north-northwest to northwest mode of stress-induced breakouts and an east-northeast to northeast mode of stress-related fracture enlargements. Fracture-related wellbore enlargements are likely associated with drilling-induced hydraulic fracturing of the wellbore or with preexisting vertical fractures or closely spaced joint sets intersecting the wellbore. The occurrence of breakouts and fracture-related wellbore enlargements does not seem dependent on any sedimentary rock type. The stress regime for the study region most likely is transitional between normal faulting at shallow depths in the Bravo dome area of the Texas Panhandle and strike-slip and reverse faulting in Oklahoma, exclusive of the Marietta basin. Bimodal-orthogonal data sets of wellbore enlargement orientations may be more likely to develop in wells in areas bounded by subparallel faults striking oblique to the SH_{max} direction (transpressional stress). An extensional (normal-faulting) stress regime in the Marietta basin may be a local fault-related stress anomaly.

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